Study of Cycle Output Improvement by Work-Fluid Including Phase Change Material

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This paper deals with the output improvement of heating and cooling cycle by using the work-fluid including phase change material. The experimental study is carried out by heat exchange between work-fluid and heat transfer surface. The work-fluid is flown to a high temperature or a low temperature heat transfer surface from the narrow path. In order to increase the amount of the heat transmission, a trace of Diethylether (boiling point 34.8 °C), as a phase change material (PCM), is added to the work-fluid. The parameters of the experiment are additive amount of PCM, the rotational speed of the displacer piston and the temperature of heat transfer surface. It is clarified that the increasing of engine cycle output is brought by the PCM addition. The effect of PCM addition is evaluated by output ratio which is defined from the experimental cycle output data. The requirements for acquiring the increasing effect of output by adding PCM are clarified.

Keywords: Phase change material, Heat transfer, Output improvement, Low temperature difference engine

Introduction

Low temperature (less than 100°C) heat as factory exhaust heat or hot spring heat is almost all thrown away. Most of the low temperature heat energy is not used at present. More than 3000 hot spring resorts with accommodation [1] exist in Japan. Although the electric power generation by using the binary cycle [2] or the thermoelectric conversion element [3] is beginning to be tried at some places, but the construction of equipment involves large costs. The installation of expensive large equipment is needed to gain the output from the low temperature heat energy. Enlarging of equipment is brought by expansion in the heat exchange part and so on. The long generated electric output selling period is needed for cost recovery.

The final purpose of this research is the development of low temperature difference drive engine supposing use in a hot spring resort as a motor for small electric power generation. In order that travelers can enjoy seeing it, the number of rotations of the engine is established at low speed. An engine cycle of this study is aimed at the Stirling cycle which can maintain high efficiency also in small size. This kind of engine has simple structure, it

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This study was performed under the Cooperative Research Program of IOES, Institute of Ocean Energy, Saga University. (Accept15004A)

Nomenclature

a	Coefficient	V	Volume (m^3, mL)
A_{dd}	Mass additional ratio to Air (mass%)	W	Output power (J/cycle)
b	Coefficient	W^*	Output power ratio (-)
Cv	Specific heat (J/(kg·K))	**Greek letters**	
D	Depth (m)	v	Kinematic viscosity (m^2/s)
G	Mass (kg)	θ	Rotation angle (rad)
H	Height between displacer piston and heat transfer surface (m, mm)	λ	Thermal conductivity (W/(m·K))
L	Length (m)	**Subscripts**	
N	Number of revolutions (r/min)	0	Initial
n	Number of times (-)	1	heating
P	Pressure (kPa)	2	cooling
ΔP	Pressure difference (kPa)	air	Air
q	Exchange heat per time (J/s)	Add	PCM including
Q	Exchange heat on heating process (J/cycle)	b	Boiling point
$S(=W_h \times D)$	Area of heat transfer surface (m^2)	$cycle$	Cycle process
St	Stroke (60 mm)	d	Diethylether
t	Time (s)	DP	Displacer piston
T	Temperature (°C)	i	Data step
ΔT	Temperature difference of heat source (K)	mc	Mean
T^*	Temperature difference ratio (-)	pr	Process
u	Mean velocity on heat transfer surface (m/s)	w	Work-fluid (Air, Air+PCM)

brings low cost, and it is easy to perform maintenance. However, it is difficult to obtain enough output by this type of engine, because of its low temperature difference. Authors found out the increasing effect of engine output by adding a little phase change material which has the boiling point between the source of high temperature and the source of low temperature in a work-fluid [4]. This paper deals with increasing of engine cycle output by using work-fluid including phase change material. The work-fluid is flown into the heating or cooling surface from the narrow path on cycle process. Some researches [5-7] on heat transfer evaluation of a work-fluid have been published, but these studies were examined by using a single phase gas as work-fluid. In order to increase the cycle output, a little amount of Diethylether ($C_4H_{10}O$, molecular weight 74.12 g/moL, density 0.7134 g/cm^3 on liquid phase, boiling point 34.8°C, colorless liquid), as a phase change material, is added to base work-fluid (air).

This study indicates the result that estimated stable drive cycle output experimentally. The experimental parameters are the number of rotations 5-20 r/min, the heat source temperature difference 45-60K and the mass composition ratio of phase change material 0-4mass%. The evaluated result is indicated as useful experimental correlation equation.

Experimental Procedure

Experimental apparatus

Fig.1 shows the schematic diagram of the experimental apparatus of this study. The experimental apparatus consists of a test section, an actuator, a data logger and the 2 set of constant temperature bathes. The test section is made of the clear acrylic resin, and thermal insulation panels 10 mm in thickness have been stuck on the internal surface. The inner size of the test section is 120 mm in height, 300 mm in width and 150 mm in length. The upper surface and the bottom surface of the test section are made of copper plate 3 mm in thickness, and are a cooling area and a heating side, respectively. The cooling and heating surface temperature are measured by 6 points of K type thermocouples that have 0.18 mm diameter. The heating and cooling surface temperature are controlled within ±0.2K of the experimental condition. The pressure change in the experiment is measured by the pressure sensor (Keyence AP-43, range 0~ +1.000 MPa, resolution 0.1 kPa, response time 1 ms) that is attaching to the acrylic test section wall. Putting the phase change material into the test section is performed using digital burette (Continuous E 2.5 mL/rev., minimum scale 0.01 mL, accuracy ±0.2%). A displacer piston that is set in the test section is connected to an actuator (Misumi single

axis robot RSD2 position accuracy ±0.02 mm, maximum load 25 kg, stroke 50–300 mm) through a SUS seal rod (3 mm in diameter), and is moved up and down by computer control. The increasing of pressure in the test section is caused by moving of displacer piston to upper side. The upper side work-fluid is flowed to bottom side by raise of displacer piston. The pressure of the test section is increased by heat exchange between work-fluid and hot heat transfer surface. The decreasing of pressure is brought by moving of displacer piston to bottom side. The heat exchange cycle experiment is carried out on each condition. Work-fluid is passed through 3 mm gaps (length of 150 mm) of side wall by up-and-down motion of a displacer piston. The process distance of a displacer piston is 60 mm.

Thermophysical properties of test work-fluid

The work-fluid of this study is air or air-diethylether mixture. Diethylether is selected as the phase change material which has the boiling point in temperature range between heating and cooling surface temperature. Table 1 shows the thermophysical properties of air and diethylether. For example, the quantity of 1.0 mass% addition at 24°C of diethylether is 0.1114 mL or 0.07953 g.

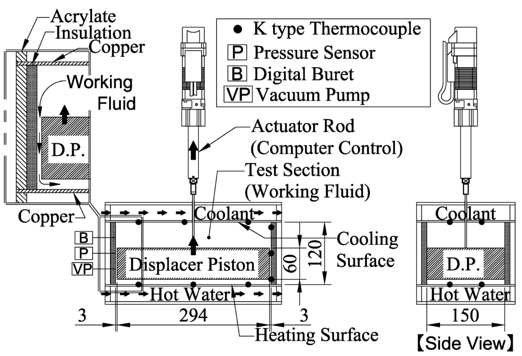

Fig. 1 Experimental apparatus.

Table 1 Physical properties of Air & Diethylether[8,9]

Work-fluid		Air	Diethylether $C_4H_{10}O$
Boiling point °C		-193	34.8
Density	Liquid	-	713.8
kg/m^3	Vapor	1.181	3.308
Heat of evaporation J/g		-	392.1
Cv J/(g·K)		0.7171	2.33:L
λ W/(m·K)		0.00257	0.129:L

Experimental procedures

The heat exchange cycle experiment is performed by the following procedures.

(1) Exhaust the work-fluid which remains to test section by vacuum pump.

(2) Air as a work-fluid of the temperature of 24°C and pressure 101.3 kPa (absolute humidity at this time is 0.0112 ± 0.0007 kg/kg*) is introduced into test section. Diethylether of specified quantity is thrown into test section by using digital burette.

(3) A cooling surface and a heating surface are set to the experimental condition temperature.

(4) The displacer piston starts to move to the upper side from the bottom side. The heat exchange cycle is continued. Then, the pressure variation reaches to the stable cycle. At this time, the pressure, heat transfer surface temperature, and work-fluid temperature of test section are measured, and it collects in a data logger.

Experimental conditions

Table 2 indicates the experimental conditions of this study. Temperature difference of heat source is set as 55–70K containing the boiling point of phase change material. The high temperature heat source is set <80°C that aims as source temperature of hot spring. The low temperature heat source is maintained 10°C. The speed of a displacer piston is set as low-speed rotation N = 5–20 r/min (u_{mc} = 0.2–0.9 m/s). The mixed rate to the work-fluid (air) of PCM (diethylether) is evaluated in A_{dd} = 0 ~ 4 mass%.

Fig.2 indicates the time history of displacer piston position and velocity at this experimental condition. The position of a displacer piston is decided by the rotation angle regardless of number of revolutions. Sine wave operation is performed in the cycle process of a displacer piston, because a displacer piston on the actual engine is controlled by rotation angle. The displacer piston operates by the computer controlled actuator. The heating process times are 1.5 seconds at 20 r/min, 3.0 seconds at 10 r/min and 6.0 seconds at 5 r/min.

Table 2 Experimental parameters and conditions

Temp. diff. bet. source ΔT K	45–60 step 5 K
High temp. source T_1 °C	55–70 step 5 K
Low temp. source T_2 °C	10
Num. of rev. N r/min (Re)	5–20 (2784–8643)
Mass composition ratio A_{dd} mass%	0–4

The cycle output is examined by using the cycle mean velocity on each number of rotations. The cycle mean velocity u_{mc} is calculated by the following equations.

$$H = St \times \sin\theta \tag{1}$$

$$u = \frac{N}{60}\frac{\Delta H \times W_{DP} \times D_{DP}}{2 \times H \times D_{DP}} \tag{2}$$

$$u_{mc} = \frac{1}{t_{pr}}\int_{-0.5\pi}^{0.5\pi} u d\theta \quad (t_{pr} \geqq 0.1\mathrm{sec}) \tag{3}$$

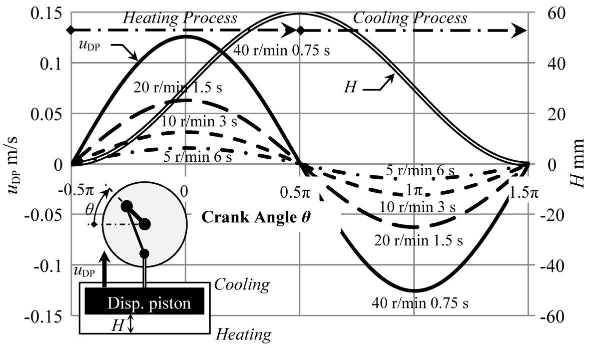

Fig. 2 Position and velocity of displacer piston on process.

Fig.3 indicates the variation of the cycle mean velocity on the heat transfer surface with number of revolutions. The cycle mean velocity is related linearly to the number of rotations.

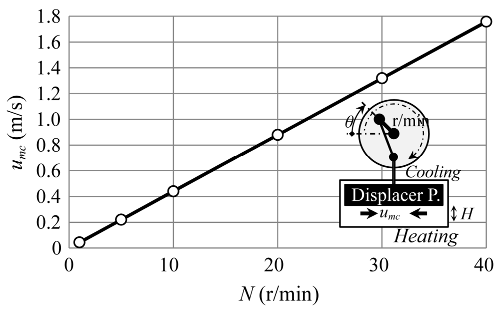

Fig. 3 Variation of cycle mean velocity with number of revolutions.

The cycle mean velocity is estimated by the following equations as Reynolds number Re (using an averaged flow velocity of the process on each number of rotations). The characteristic length is set to 1/2 (L = 0.15 m) of heat transfer surface width, because the work-fluid flows into the center from both ends. The amount of additional phase change material is very little, so that the dynamic viscosity of air is used for calculation.

$$Re = \frac{u_{mc} L}{\nu_{air}} \tag{4}$$

The quantity of heat which a work-fluid receives in heat exchange process is calculated by the following equation with the application of a constant-volume change.

$$q = G_w C_w \left(\frac{P}{P_0} T_i - T_{i-1} \right) \tag{5}$$

In which, C_w and G_w are the specific heat at constant volume and the mass of work-fluid. These values are calculated by using the thermophysical properties of composition.

$$C_w = Cv_{air} G_{air} + Cv_d G_d \tag{6}$$

$$G_w = (1 - Add) \times G_{air} + Add \times G_d \tag{7}$$

The quantity of heat in a cycle which a work-fluid receives is calculated by next integral equation. The obtained heat amount equals output per cycle.

$$Q = \oint q\, d\theta = W \tag{8}$$

The output improvement effect by the PCM addition is estimated by the output ratio. The output ratio is defined by next equation.

$$W^* = W_{Add} / W_{aic} \tag{10}$$

The temperature difference ratio is calculated by the following equation using PCM boiling point.

$$T^* = (T_1 - T_2)/(T_b - T_2) \tag{11}$$

Experimental Results and Discussions

Indicator (ΔP-V) diagram

Fig.4 shows the relationship between the pressure difference and the heating side volume (indicator ΔP-V diagram) at A_{dd} = 0 mass% (Air), N = 20 r/min, ΔT = 50K. The cycle pressure changes to the high pressure from the start of experiment. The stable cycle focusing on 0kPa is observed at $n \geqq 22$.

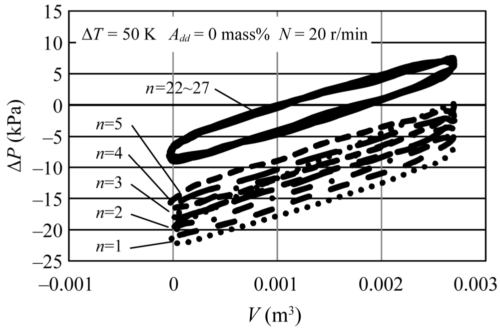

Fig. 4 Relationship between the differential-pressure and the heating side volume (A_{dd} = 0 mass%, N = 20 r/min, ΔT = 50 K)

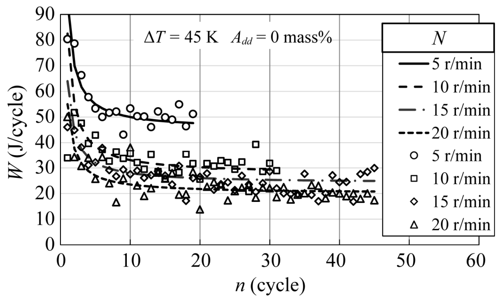

Fig. 5 Variation of the output per cycle with the times of driving cycle. (A_{dd} = 0 mass%, ΔT = 45K)

Variation of the output per cycle with the number of cycle is shown in Fig.5. The output per cycle is calculated by cycle integration of each cycle. The experimen-

tal data are indicated by the plots in this figure. The curved lines show the approximation values that are obtained from experimental data. Output reaches the stable value by driving for more than 80 seconds in spite of the condition. Therefore the data of drive time after 120 seconds as the stable cycle are used in this study.

Cycle output by using air as work-fluid

Fig.6 shows the variation of the output per cycle with the number of revolutions at A_{dd} = 0 mass% (air). Cycle output decreases with the increasing of the number of rotations. Because the decreasing of heat exchange time is brought by the increasing of number of rotations.

Fig.7 shows the variation of the output per cycle with the temperature difference of heat source at A_{dd} = 0 mass% (air). Cycle output increases with the increase of temperature difference of heat source.

The experimental data of cycle output by using air (A_{dd} = 0 mass%) as work-fluid is correlated as following equations. The values obtained by the equations are equal to the experimental data within ± 10 %.

$$W_{air} = a\left(\frac{1}{N}\right) + b \qquad (5 \leqq N \leqq 20) \qquad (12)$$

$$a = 10.1\Delta T - 230 \qquad (45 \leqq \Delta T \leqq 60) \qquad (13)$$

$$b = 0.0405\Delta T^2 - 3.81\Delta T + 97.0 \quad (45 \leqq \Delta T \leqq 60) \quad (14)$$

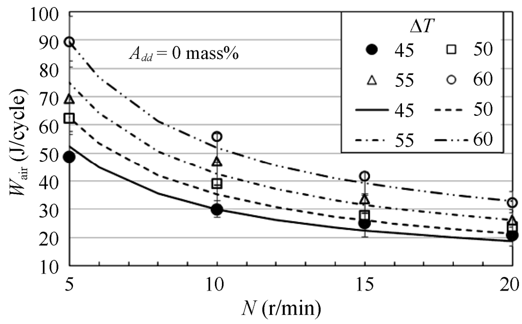

Fig. 6 Variation of the output per cycle with the number of revolutions. (A_{dd} = 0 mass%)

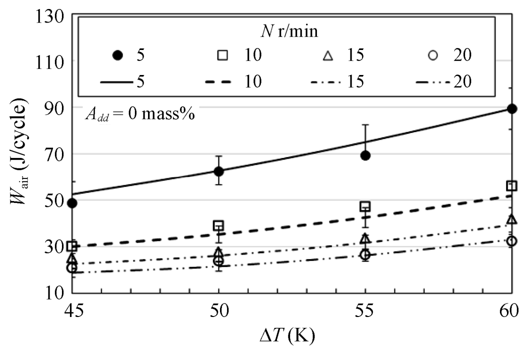

Fig. 7 Variation of the output per cycle with the temperature difference of heat source. (A_{dd} = 0 mass%)

Cycle output by using air-PCM mixture as work-fluid

Fig.8 indicates the relationship between the output per cycle and the cycle time or the number of rotations at A_{dd} = 0.5mass%. Output per cycle is decreased with the increasing of number of rotations.

Fig.9 indicates the variation of output ratio with temperature difference ratio at N=15 r/min (Re = 6870). The plots in the figure indicate experimental value. The lines in the figure indicate the value calculated by the following experimental correlation equation. Output ratio shows the high value at the range of the temperature difference ratio ΔT^* =0.8–1.2.

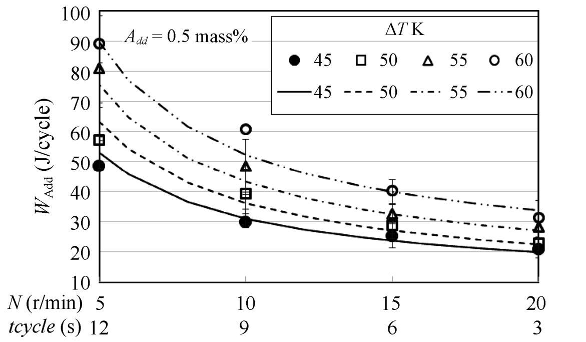

Fig. 8 Relationship between the output per cycle and the cycle time or the number of rotations. (A_{dd} = 0.5 mass%)

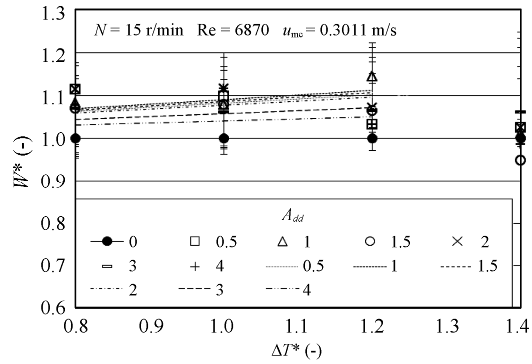

Fig. 9 Relationship between the output ratio and the heat source temperature difference ratio. (N = 15 r/min)

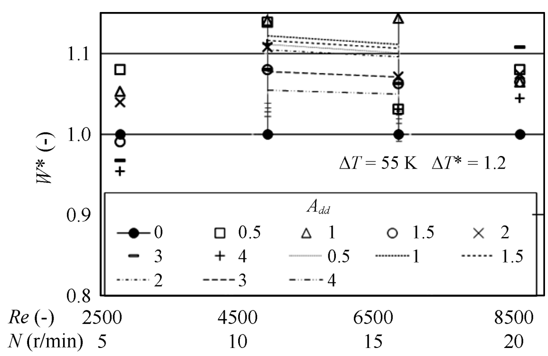

Fig. 10 Variation of the output ratio with Reynolds number or the number of rotations. (ΔT = 55K)

Fig.10 shows the relationship between the output ratio and the Reynolds number or the number of rotations at T^* = 1.2. It is observed that the high output ratio range is Re = 4945–6870 (N = 10–15 r/min).

Fig.11 indicates the relationship between the output ratio and PCM additional ratio at Re = 6870 (N = 15 r/min). The high output ratio is indicated at the range of A_{dd} = 0.5–1 mass%.

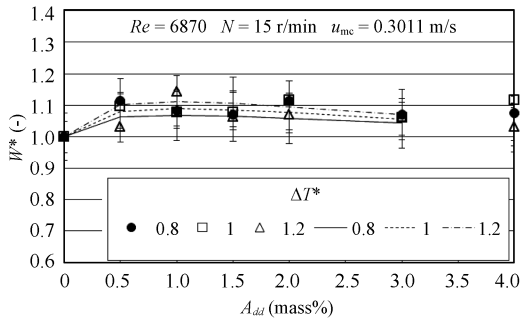

Fig. 11 Relationship between the output ratio and the PCM additional ratio. (N = 15 r/min)

Output ratio W^* is correlated by A_{dd}, ΔT^* and Re. Therefore, the following equation is obtained. Applicable range of the equation is Re = 4945~8643 (N = 10~20 r/min), ΔT^* = 0.8~1.2 (ΔT = 45~55K) and A_{dd} = 0.5~3 mass%.

$$W^* = \frac{W_{Add}}{W_0} = \frac{\frac{1}{23.10} \cdot A_{dd}^{\frac{1}{2}} \cdot e^{\frac{Add}{2}}}{\Delta T^{*-\frac{6}{5}} \cdot Re^{\frac{7}{25}}} + 1.0000 \qquad (15)$$

Conclusions

Experimental study of the heat exchange cycle by using the work-fluid including PCM (diethylether) is carried out, and the following conclusions are obtained.

Output improvement by PCM addition work-fluid was observed in the heat exchange cycle.

The optimum range of condition (mass composition ratio of PCM, speed and temperature) for the cycle output improvement was indicated .

The useful experimental correlation equation was suggested by the cycle output ratio.

Acknowledgement

This study was performed under the Cooperative Research Program of IOES, Institute of Ocean Energy, Saga University. (Accept15004A)

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